

Evolution of the Black Hole – Bulge Relationship in QSOs

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Abstract

QSOs allow study of the evolution of the relationship between black holes in galactic nuclei and their host galaxies. The black hole mass M_{BH} can be derived from the widths of the broad emission lines, and the stellar velocity dispersion σ_* of the host galaxy can be inferred from the narrow emission lines. Results based on [O III] and [O II] line widths indicate that the $M_{\text{BH}} - \sigma_*$ relationship, at redshifts up to $z \approx 2$, is consistent with no evolution or an increase of up to ~ 0.5 dex in M_{BH} at fixed σ_* . CO line widths offer an estimate of σ_* for luminous QSOs at high redshifts. The available objects from $z \approx 4$ to 6 have very massive black holes, $M_{\text{BH}} \sim 10^{9.5} M_{\odot}$, but their CO line widths suggest much smaller host galaxies than would be expected by the local $M_{\text{BH}} - \sigma_*$ relationship. The most massive black holes must continue to reside in comparatively modest galaxies today, because their number density inferred from QSO statistics exceeds the present-day abundance of proportionally massive galaxies.

Key words: galaxies: active galactic nuclei, supermassive black holes

1. Introduction

The study of black hole demographics has added a new dimension to research involving active galactic nuclei (AGN). This is rooted in two developments of recent years. The first is the availability of measurements of supermassive black holes in nearby galaxies, involving observations of stellar and gaseous motions with *HST* along with other techniques (reviews by Kormendy & Gebhardt 2001; Ferrarese & Ford 2004; Combes 2005). This has led to the realization that M_{BH} is closely correlated with the luminosity and especially the velocity dispersion of the bulge component of the host galaxy (Gebhardt et al. 2000; Ferrarese & Merritt 2000).

The local $M_{\text{BH}} - \sigma_*$ relationship is given by

Tremaine et al. (2002) as

$$M_{\text{BH}} = (10^{8.13} M_{\odot})(\sigma_*/200 \text{ km s}^{-1})^{4.02}. \quad (1)$$

The rms dispersion of only ~ 0.3 in $\log M_{\text{BH}}$ in this relationship suggests a fundamental connection between the evolution of supermassive black holes and their host galaxies. The formation and evolution of supermassive black holes has become a focus of theoretical study (review by Haiman & Quataert 2004; Croton 2005, and references therein).

The second development is the ability to estimate M_{BH} in AGN based on evidence that the broad emission lines come from gas orbiting the black hole at a radius that can be estimated from the continuum luminosity (Kaspi et al. 2005, and references therein). Central black hole masses in AGN can easily be estimated in this fashion, al-

lowing demographic studies and providing insight into AGN physics. Results below assume a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Black Holes in QSOs

Direct measurements of nuclear black holes, based on spatially resolved measurements of the velocities of stars and gas within the gravitational sphere of influence of the hole, are limited to nearby objects with negligible look-back times. QSOs afford an opportunity to study the $M_{\text{BH}} - \sigma_*$ relationship as a function of cosmic time. However, this requires a measurement of the luminosity or velocity dispersion of the host galaxy in addition to the black hole mass. The host galaxy luminosity and the stellar velocity dispersion are difficult to measure directly at high redshift, given the glare of the active nucleus. An alternative approach is to estimate σ_* through the use of some surrogate involving emission lines of gas orbiting in the host galaxy.

Nelson & Whittle (1996) found that, on average, the width of [O III] tracks the stellar velocity dispersion, $\sigma_{[\text{O III}]} \equiv \text{FWHM}([\text{O III}])/2.35 \approx \sigma_*$. This is supported by the agreement of M_{BH} and $\sigma_{[\text{O III}]}$ in nearby AGN with the local $M_{\text{BH}} - \sigma_*$ relationship (Nelson 2000). Further support comes from the study of Bonning et al. (2005), who found overall agreement between $\sigma_{[\text{O III}]}$ in low redshift QSOs and the value of σ_* implied by the measured host galaxy luminosity and the Faber-Jackson relation. The rms scatter is ~ 0.13 in $\log \sigma_{[\text{O III}]}$ at fixed host luminosity. This suggests that $\sigma_{[\text{O III}]}$ may be a useful proxy for σ_* in statistical studies, although not for individual objects.

Shields et al. (2003) carried out such a program using the narrow [O III] $\lambda 5007$ emission line of QSOs. They collected measurements of the widths of the broad H β line and narrow [O III] line in QSOs ranging in redshift from $z < 0.1$ to $z = 3.3$. Black hole masses were derived from the expression

$$M_{\text{BH}} = (10^{7.69} M_\odot) v_{3000}^2 L_{44}^{0.5}, \quad (2)$$

where $v_{3000} \equiv \text{FWHM}(\text{H}\beta)/3000 \text{ km s}^{-1}$ and

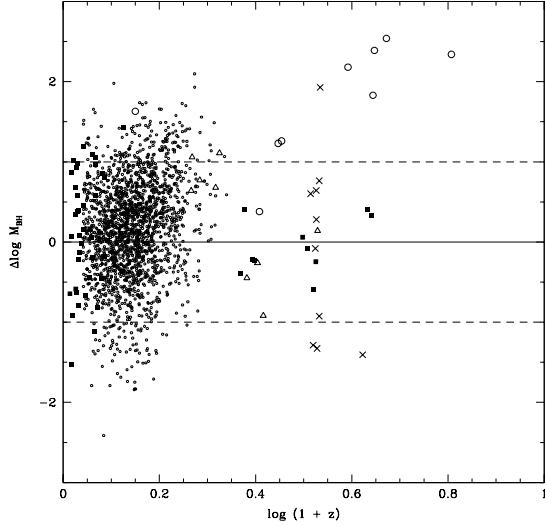


Fig. 1. Deviations from the local $M_{\text{BH}} - \sigma_*$ relationship, $\Delta \log M_{\text{BH}}$, as a function of redshift. Filled squares: H β - [O III] results from Shields et al. (2003); small circles: H β - [O III] and Mg II - [O II] results from Salviander et al. (2006); open triangles: [O III] measured from spectra by Sulentic et al. (2004, see text and Table 1); crosses: H β - [O III] results from Netzer et al. (2004) and Shemmer et al. (2004); large open circles: high redshift CO QSOs from Shields et al. (2006), who suggest a recalibration downward by ~ 0.5 from the values shown.

$L_{44} \equiv \nu L_\nu/(10^{44} \text{ erg s}^{-1})$, the continuum luminosity at 5100 Å, based on Kaspi et al. (2000). They expressed their results in terms of the deviation of an object's actual M_{BH} from the value M_σ expected on the basis of Equation 1 using $\sigma_{[\text{O III}]}$. We follow their use of $\Delta \log M_{\text{BH}} \equiv \log M_{\text{BH}} - \log M_\sigma$. Figure 1 shows the results for $\Delta \log M_{\text{BH}}$ as a function of redshift. There is considerable scatter, but overall the objects show little systematic offset from Equation 1 as a function of redshift. Shields et al. concluded that M_{BH} at $z \sim 2$ differs by less than 0.5 dex from the present day value expected for a given σ_* . However, the high redshift objects have larger masses ($M_{\text{BH}} \approx 10^{9.6} M_\odot$) than the low redshift objects ($\sim 10^{8.3} M_\odot$), so the evolutionary comparison involves some disparity in mass.

Salviander et al. (2006; see also these proceedings) used these methods to assess the evolution of the $M_{\text{BH}} - \sigma_*$ relationship in the QSOs in Data

Release 3 (DR3) of the Sloan Digital Sky Survey¹ (SDSS; Abazajian et al. 2005). They used H β and [O III] for redshifts up to 0.8, and the broad Mg II λ 2800 and narrow [O II] λ 3727 emission lines to reach redshifts up to 1.2. Their results, included in Figure 1, nominally show a rise of ~ 0.5 in $\Delta \log M_{\text{BH}}$ from $z \sim 0.3$ to $z \sim 1.0$. However, they show that two sources of bias contribute to this apparent evolution. (1) The scatter in the local $M_{\text{BH}} - \sigma_*$ relationship causes some galaxies to harbor exceptionally large black holes. If these are fueled in proportion to their mass, their high luminosities cause them to be over-represented in the QSO sample. (2) There is a tendency in data of marginal signal/noise quality to fail to detect wider lines, over-representing narrower [O III] lines in the sample. Subtracting these biases, which both act to give an increase in $\Delta \log M_{\text{BH}}$ with redshift, Salviander et al. find a residual evolution of 0.3 ± 0.3 in $\Delta \log M_{\text{BH}}$ at redshift unity.

CO emission lines afford an opportunity to study QSO host galaxies at higher redshifts. Shields et al. (2006) used $\sigma_{\text{CO}} \equiv \text{FWHM}(\text{CO})/2.35$ together with M_{BH} derived from the broad Mg II and [C IV] lines to assess the $M_{\text{BH}} - \sigma_*$ relationship in QSOs up to $z = 6.4$. They find large black holes ($\sim 10^{9.5} M_{\odot}$) that are at least an order of magnitude larger than expected for the CO line width (see Figure 1). These giant black holes in the early universe evidently reside in comparatively modest galaxies, as found for the case of SDSS J1148+5251 ($z = 6.4$) by Walter et al. (2005).

Figure 1 summarizes a variety of measurements of $\Delta \log M_{\text{BH}}$ as a function of redshift. Included are a number of $z \sim 2$ QSOs from Netzer et al. (2004) and Shemmer et al. (2004), as selected by Bonning et al. (2005). The six radio-loud objects have a mean $\Delta \log M_{\text{BH}}$ of -0.4 . Also shown are nine QSOs from the study of Sulentic et al. (2004). For these, we have measured the [O III] width from the VLT spectra of Sulentic et al., kindly provided by P. Marziani (personal communication). We made a direct measurement of the FWHM of the λ 5007 line for those objects having adequate [O III] intensity and not having excessive [Fe II] emission, keeping nine of 17 objects. We measured the con-

tinuum flux at 5100 Å rest wavelength from the spectra, derived the luminosity (for our cosmology), and calculated M_{BH} from Equation 2 taking FWHM(H β) from Sulentic et al. The VLT measurements have a mean $\Delta \log M_{\text{BH}} = 0.31$, or 0.48 including only the radio-quiet objects. Altogether, these results are consistent with the conclusion of Shields et al. (2003) that there is relatively little evolution of the $M_{\text{BH}} - \sigma_*$ relationship between $z \sim 2$ and the present, albeit with considerable scatter.

Table 1

Width of narrow [O III] line in QSOs measured from the spectra by Sulentic et al. (2004), along with M_{BH} derived from Equation 2 (see text). Absolute luminosity νL_{ν} is given at rest wavelength λ 5100 for our adopted cosmology. HE 0003, 0005, 0454, and 2349 are radio-loud (Sulentic et al. 2004).

QSO	z	$\log \sigma_{[\text{O III}]}$	$\log \nu L_{\nu}$	$\log M_{\text{BH}}$	$\Delta \log M_{\text{BH}}$
HE 0003	1.077	2.41	46.12	9.26	0.68
HE 0005	1.412	2.73	46.25	9.40	-0.45
HE 0048	0.847	2.41	45.49	9.23	0.64
HE 0248	1.536	2.76	47.49	9.73	-0.25
HE 0331	1.115	2.34	46.40	9.41	1.11
HE 0454	0.853	2.18	45.83	8.71	1.06
HE 2340	0.922	2.34	46.18	9.07	0.77
HE 2349	1.604	2.83	46.36	9.35	-0.91
HE 2355	2.382	2.67	46.71	9.77	0.15
Average	1.305	2.52	46.31	9.33	0.31

3. Does [O III] track σ_* in AGN?

We noted above some indications that $\sigma_{[\text{O III}]}$ may be a useful surrogate for σ_* in a statistical sense. Figure 2, based on Bonning et al. (2005), compares $\sigma_{[\text{O III}]}$ with σ_* in a wide variety of AGN. Because of the scatter in $\sigma_{[\text{O III}]}$ at fixed σ_* , a wide dynamic range in σ_* is needed to clarify the overall trend. For lower luminosity AGN (Seyfert galaxies), direct measurements of σ_* are used. For QSOs, in which σ_* is difficult to measure, σ_* is inferred from M_{BH} and Equation 1. We include here the VLT results of Table 1 and, at very low σ_* the

¹ The SDSS Web site is <http://www.sdss.org/>.

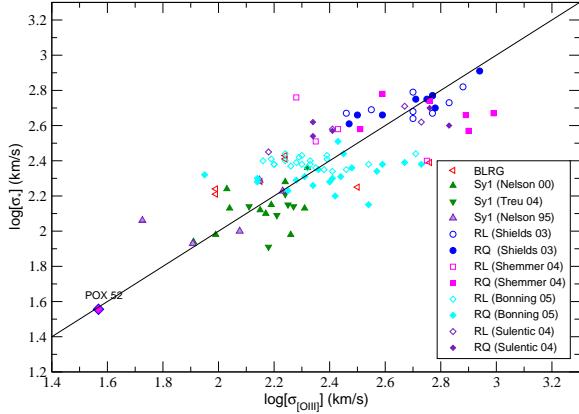


Fig. 2. Correlation between $\sigma_{[\text{O III}]}$ and σ_* for AGN, from Bonning et al. (2005) with the addition of POX 52 (Barth et al. 2004) and the VLT data from Table 1. See Bonning et al. for details and references. This figure follows Bonning et al. in using a slightly different formula for M_{BH} from Equation 2.

dwarf Seyfert galaxy POX 52 (Barth et al. 2004). There is a clear trend of increasing $\sigma_{[\text{O III}]}$ with σ_* , consistent with the idea that $[\text{O III}]$ is a valid, if noisy, surrogate.

Greene & Ho (2005) compare σ_* with the widths of several narrow emission lines in a sample of narrow-line Seyfert galaxies from SDSS. They find that $\sigma_{[\text{O II}]}$ agrees in the mean with σ_* . However, $\sigma_{[\text{O III}]}$ exceeds σ_* by ~ 0.13 dex unless a correction is made for the extended blue wing of the $[\text{O III}]$ profile. In contrast, Salviander et al. (2006) find that $\sigma_{[\text{O III}]}$ and $\sigma_{[\text{O II}]}$ agree within a few hundredths of a dex in their sample of SDSS QSOs, without any correction for the blue wing. It is important to clarify the effect of the blue wing on $\sigma_{[\text{O III}]}$ in various classes of AGN, and how best to correct for it.

4. Homelessness Amongst the Largest Black Holes

Several authors have noted that the largest black hole masses, inferred in the most luminous QSOs from broad line widths or the Eddington limit, exceed the largest values of M_{BH} found in the local universe, and the implied values of σ_* by Equation 1 exceed the largest σ_* values in galaxies (Netzer 2003; Wyithe & Loeb 2003; Shields & Gebhardt 2004).

If the black hole masses are correct, this implies a breakdown of the local $M_{\text{BH}} - \sigma_*$ relationship at high M_{BH} .

McLure & Dunlop (2004), in a study of SDSS QSOs, find values of M_{BH} up to $\sim 10^{10} M_{\odot}$, but they dismiss the largest values as resulting from the scatter in deriving M_{BH} from expressions like Equation 2. Thus they conclude that black holes in QSOs are consistent with the maximum mass $M_{\text{BH}} \sim 10^{9.5} M_{\odot}$ found in giant elliptical galaxies, such as M87 (Tremaine et al. 2003). There is indeed scatter in the BLR radius as a function of luminosity (Kaspi et al. 2000), which underlies Equation 1. However, we argue here that the large values of M_{BH} in the most luminous quasars are likely real. In the QSO sample of Shields et al. (2003), there are eight radio-quiet objects with $\log \nu L_{\nu}(5100) \geq 46.6$; and of these, five have $\log M_{\text{BH}} \geq 9.7$, substantially exceeding the largest M_{BH} in local galaxies. Here we are dealing with a majority of the objects of a class selected by a criterion that does not involve the scatter in Equation 2. Thus, one cannot appeal to scatter to dismiss the large values. These six objects have an average $\log L/L_{\text{Ed}} \approx -0.1$, suggesting that M_{BH} cannot be much less than derived from the $\text{H}\beta$ width.

What is the present-day density of these giant black holes? From the QSO luminosity function of Boyle et al. (2003), we estimate the space density of QSOs with $\log \nu L_{\nu}(5100) > 46.6$ to be $\sim 6 \text{ Gpc}^{-3}$ (comoving) at $z = 2$. Since they are nearly at the Eddington limit, we take their lifetime to be the Salpeter e-folding time of 50 million years (efficiency $0.1c^2$). Applying the above fraction of 5/8 and taking an effective QSO epoch of 3 billion years (Warren, Hewitt, & Osmer 1994), we find the density of relic black holes over 5 billion M_{\odot} to be $\sim 10^{2.3} \text{ Gpc}^{-3}$.

By the local $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - M_{\text{bulge}}$ relationships (Kormendy & Gebhardt 2001), a black hole of 5 billion M_{\odot} corresponds to $\sigma_* \approx 500 \text{ km s}^{-1}$ and $M_{\text{bulge}} \approx 10^{12.6} M_{\odot}$. The largest local giant ellipticals (e.g., M87) have $\sigma_* \approx 350 \text{ km s}^{-1}$ (Faber et al. 1997), and the velocity dispersion function of SDSS galaxies ends at $\sim 400 \text{ km s}^{-1}$ (Sheth et al. 2003). Bernardi et al. (2006) find only two or three candidate galax-

ies in SDSS with $\sigma_* > 500 \text{ km s}^{-1}$ in a volume $\sim 0.5 \text{ Gpc}^3$ among the objects for which they find the evidence for superposition to be weakest. The nearest black hole with mass $\geq 10^{9.7} \text{ M}_\odot$ should be at a distance of $\sim 100 \text{ Mpc}$ and redshift of $\sim 7000 \text{ km s}^{-1}$. Wyithe (2006) and Wyithe & Loeb (2003) reach a similar conclusion based on the assumption that the most luminous QSOs shine at the Eddington limit. This distance corresponds to the largest cD galaxies, such as NGC 6166 in Abell 2199 and NGC 7720 in Abell 2634. Such galaxies may be a logical place to look for a 5 billion solar mass hole. However, such a black hole in NGC 6166 or NGC 7720 would violate Equation 1, since these galaxies have central velocity dispersions $\sim 350 \text{ km s}^{-1}$ (Tonry 1984).

The space density of galaxy clusters with $\sigma_v > 500 \text{ km s}^{-1}$ (Bahcall et al. 2003) exceeds by an order of magnitude our derived density of black holes over 5 billion solar masses. Ample dark matter halos at this velocity dispersion exist in the modern universe, but not individual galaxies. Evidently, at this value of σ_* , the physics of baryon assembly is such that giant black holes can form in the early universe but the growth of their host galaxies is stunted. Perhaps this involves the disruptive effect of the QSO luminosity (Benson et al. 2003; Wyithe & Loeb 2003; di Matteo et al. 2005). The giant holes in the CO quasars discussed above appear destined to remain in galaxies of comparatively modest proportions.

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